STAR Physics Program at RHIC

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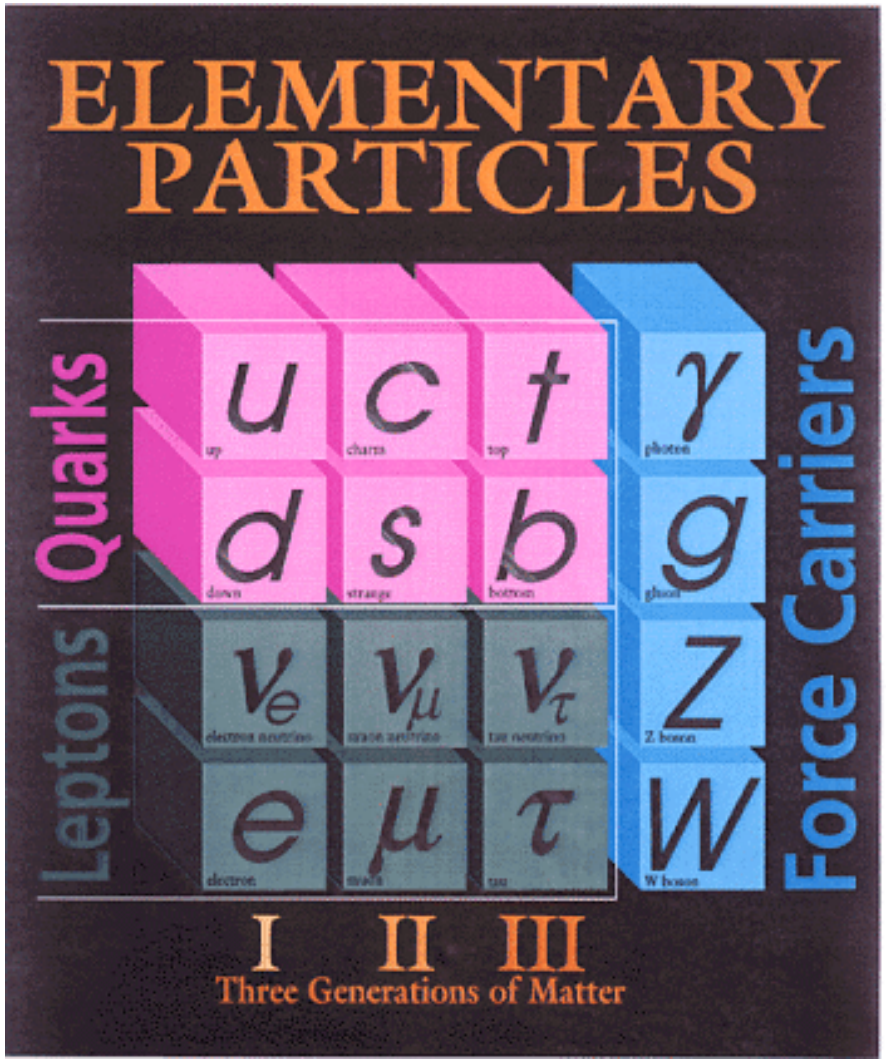
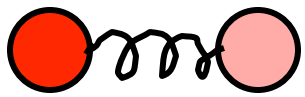
Basics on Quantum Chromodynamics

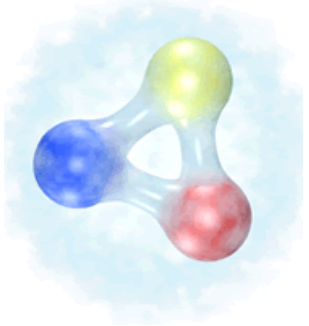


1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.
2) Gluons hold quarks together to from hadrons:

meson

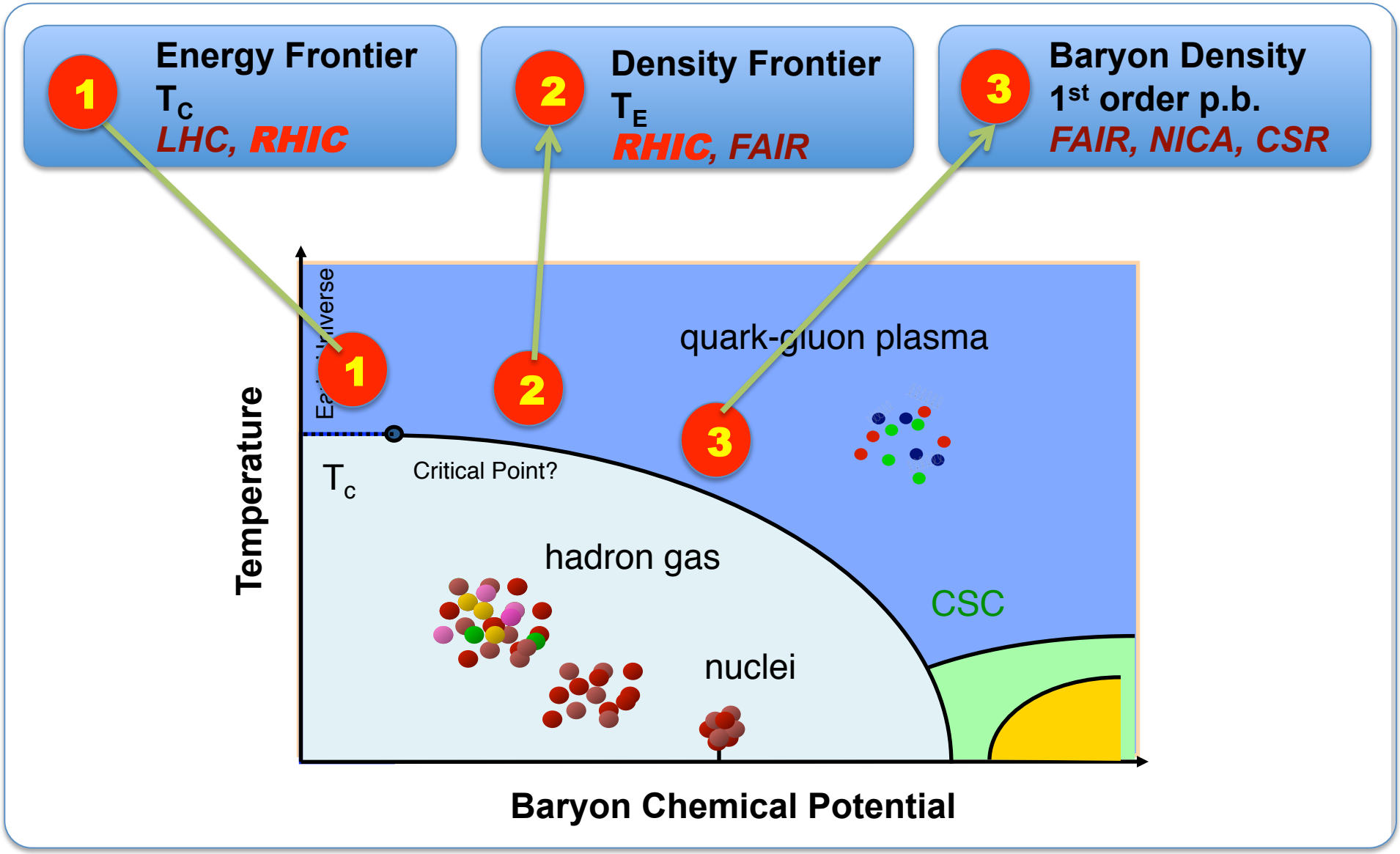


baryon

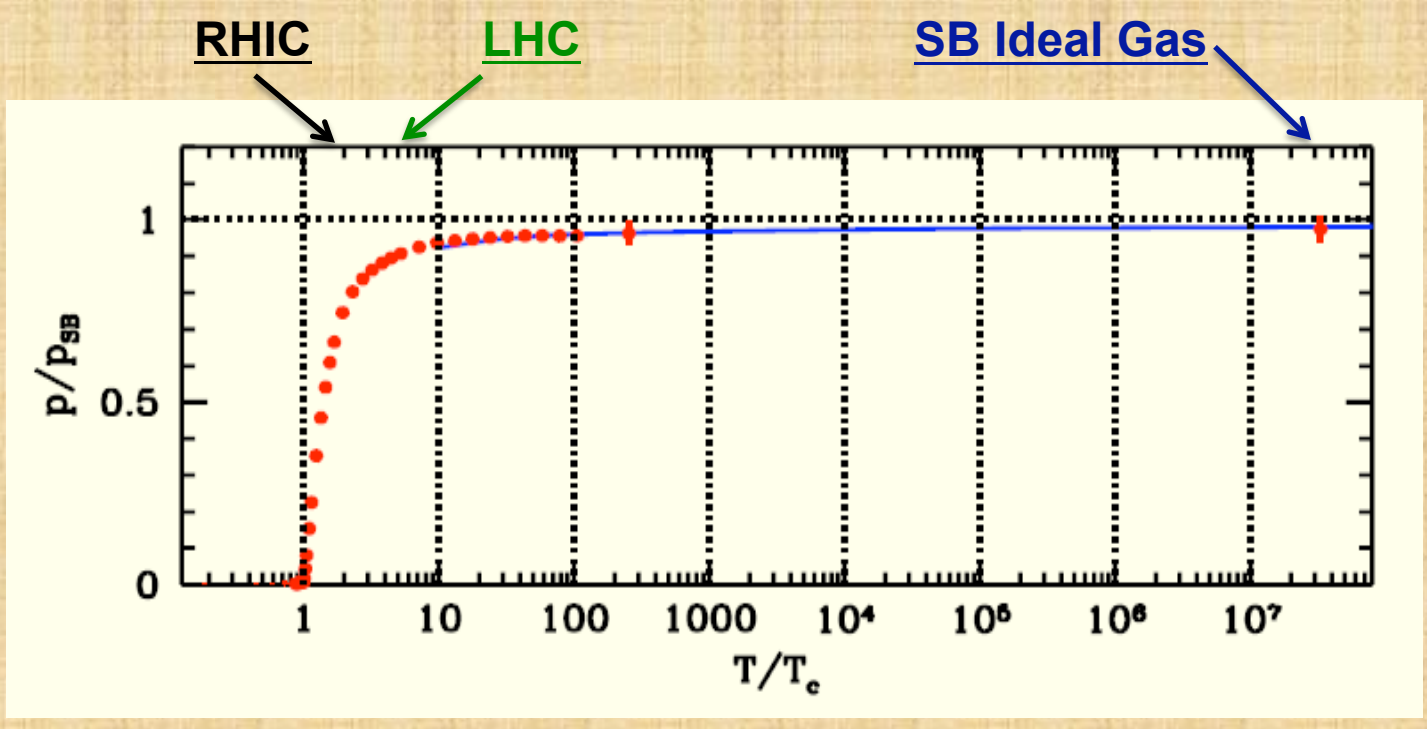


3) Gluons and quarks, or partons, typically exist in a color singlet state: ***confinement.***

High-Energy Nuclear Collisions



QCD Thermodynamics



1) At $\mu_B = 0$: cross over, $150 < T_c < 200$ MeV
2) The SB ideal gas limit: $T/T_c \sim 10^7$
3) T_{ini}(LHC) ~ 2-3*T_{ini}(RHIC)
4) **Thermodynamic evolutions are similar for RHIC and LHC***

Zoltan Fodor, Lattice 2007

STAR Physics Focus

Structure of Nucleon

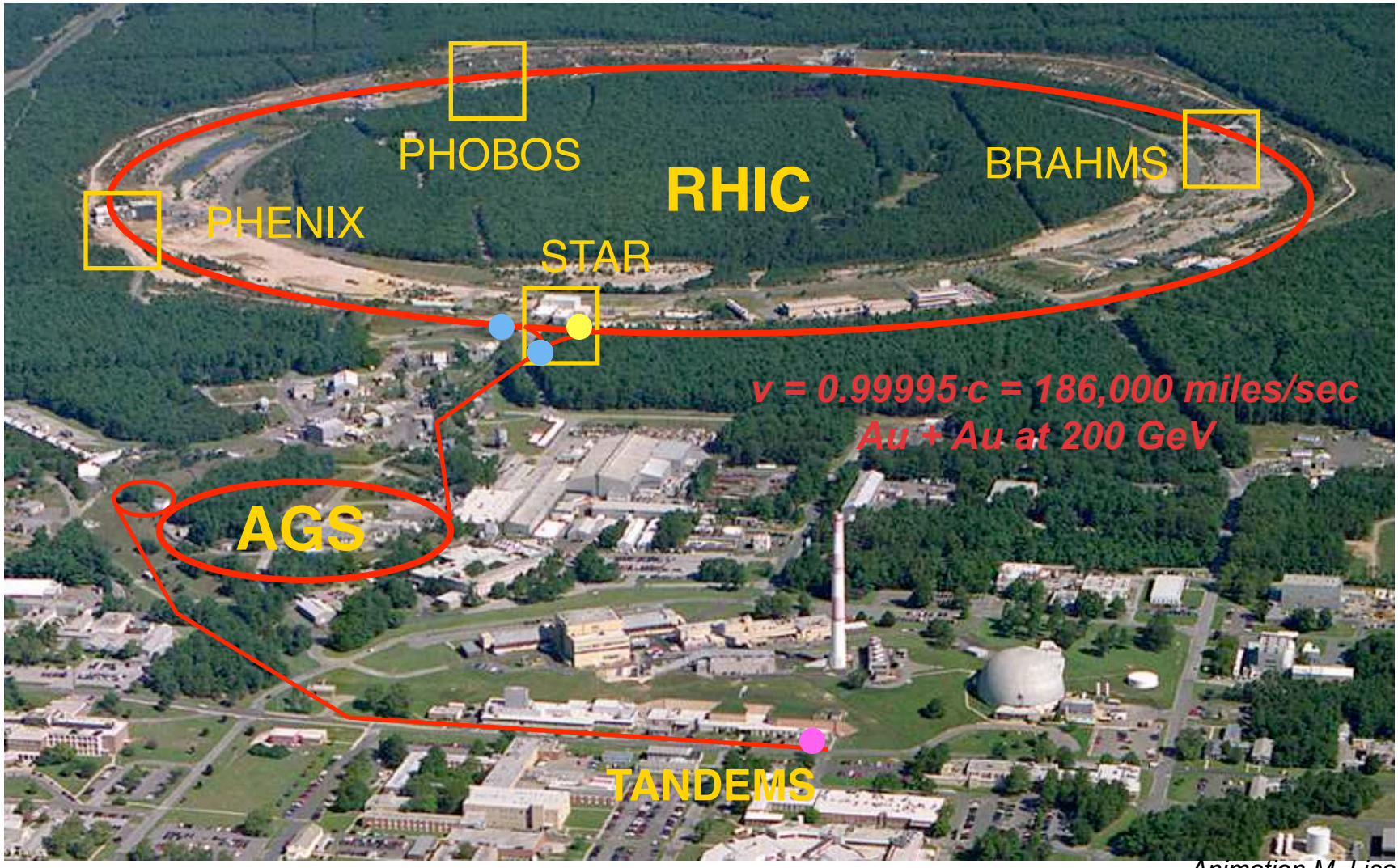
Structure of Cold Nuclear Matter

Structure of Hot/Dense Matter

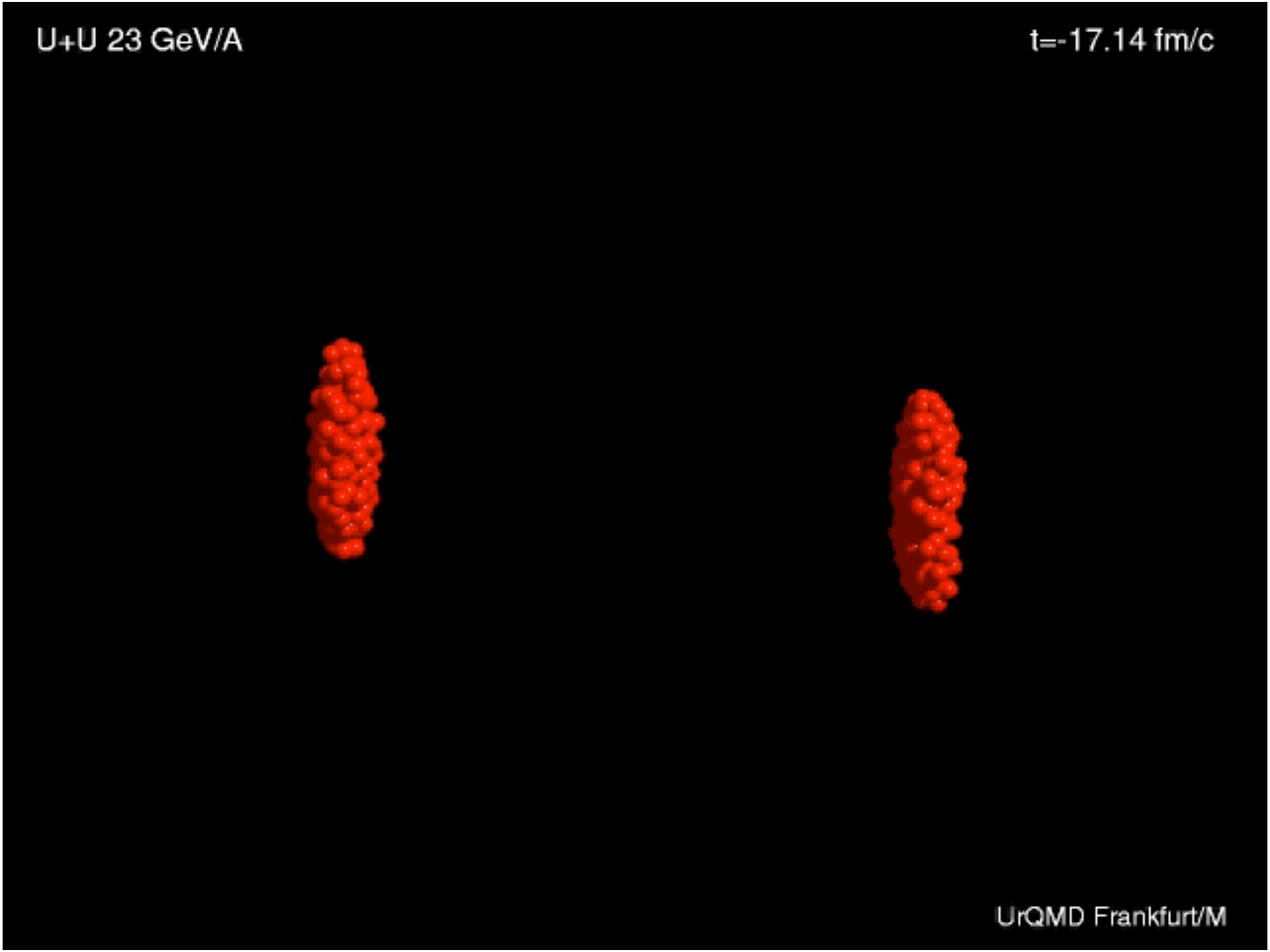
Matter with partonic degrees of freedom. Theory of QCD.

Relativistic Heavy Ion Collider (RHIC)

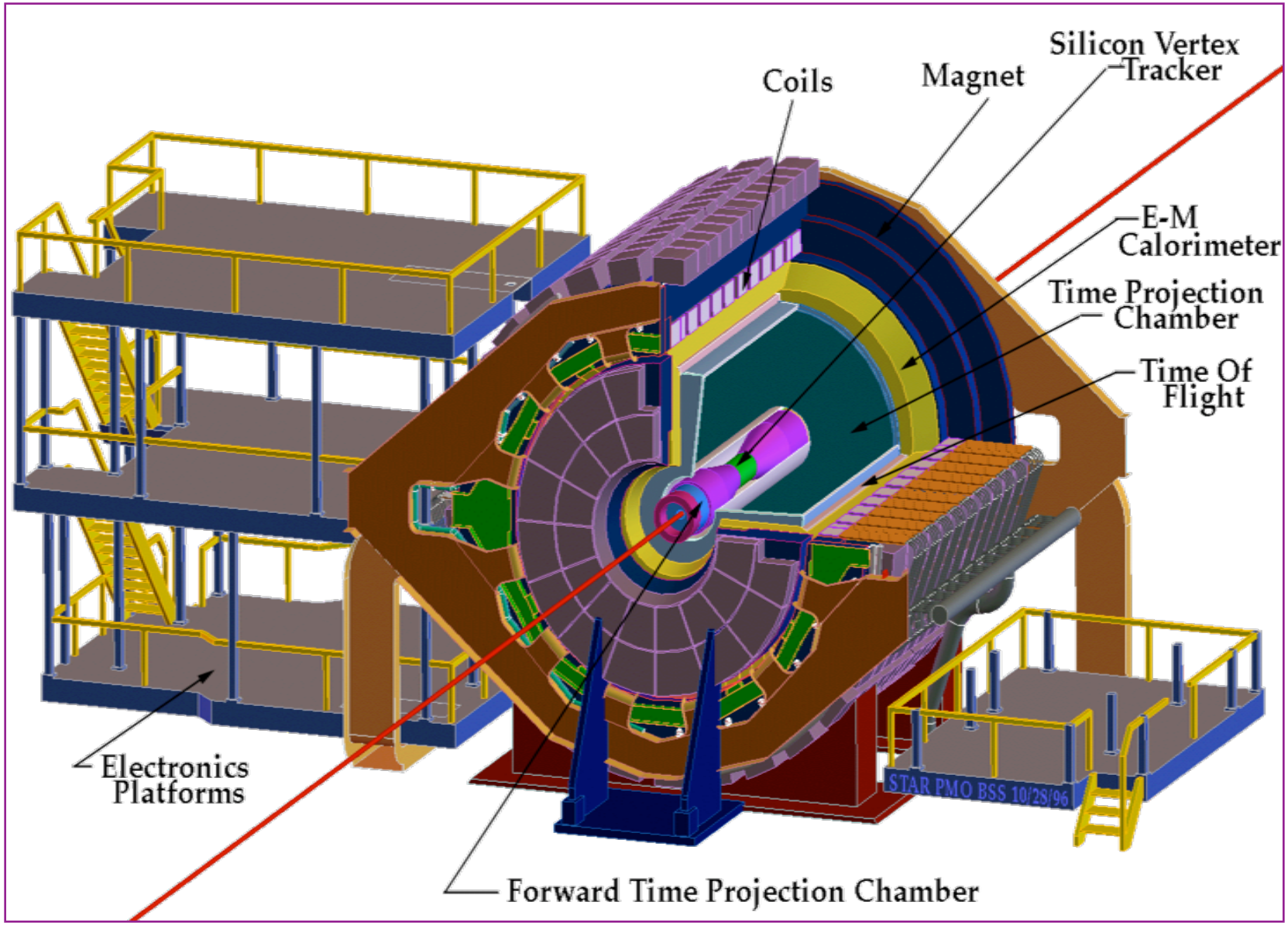
Brookhaven National Laboratory (BNL), Upton, NY



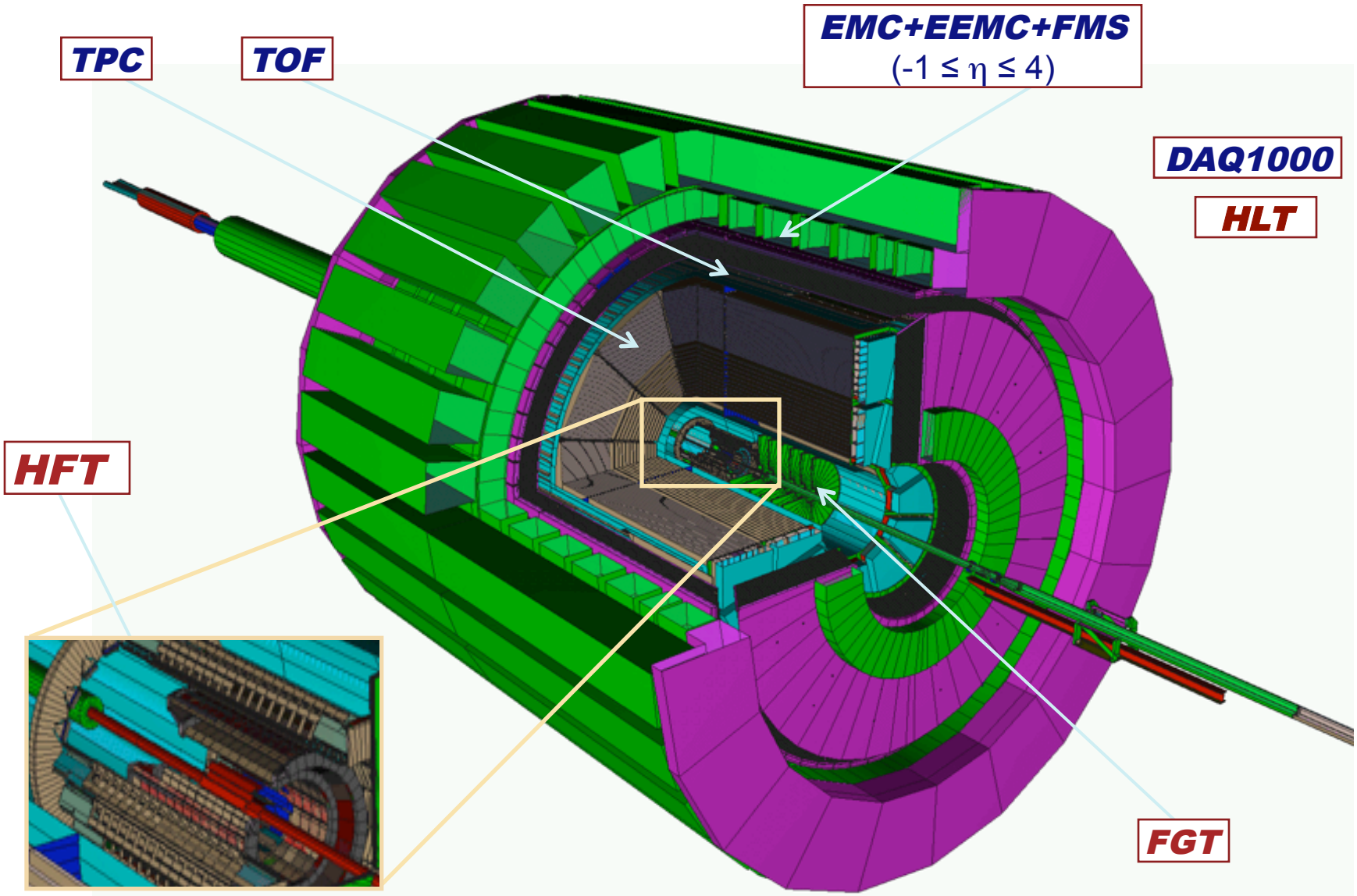
Animation M. Lisa

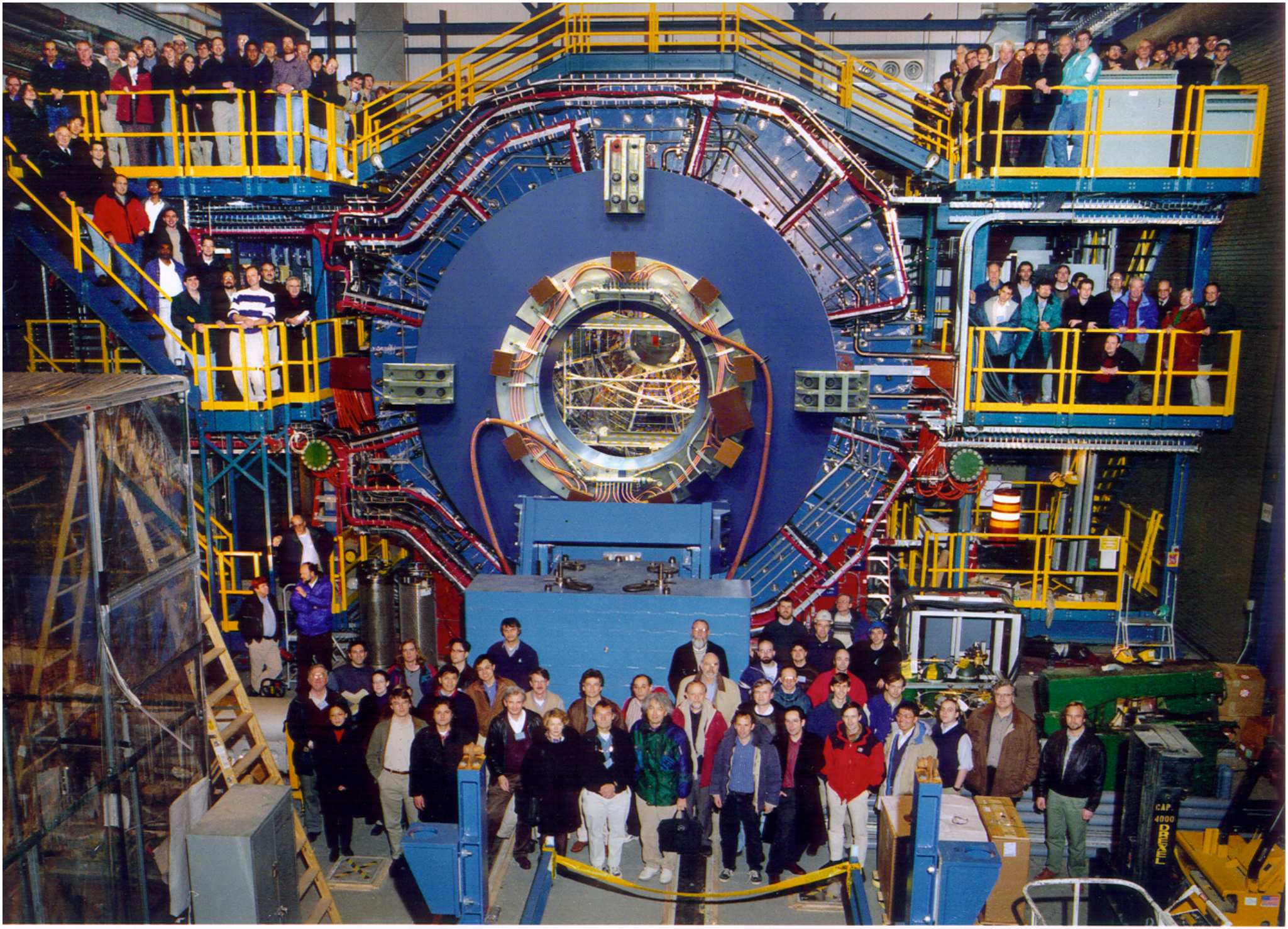

U+U 23 GeV/A
t=-17.14 fm/c
UrQMD Frankfurt/M

STAR Detectors



STAR Detectors: *Full 2π particle identification!*




CAP.
4000
Caterpillar

Outline

1) Spin program

2) Heavy-Ion program

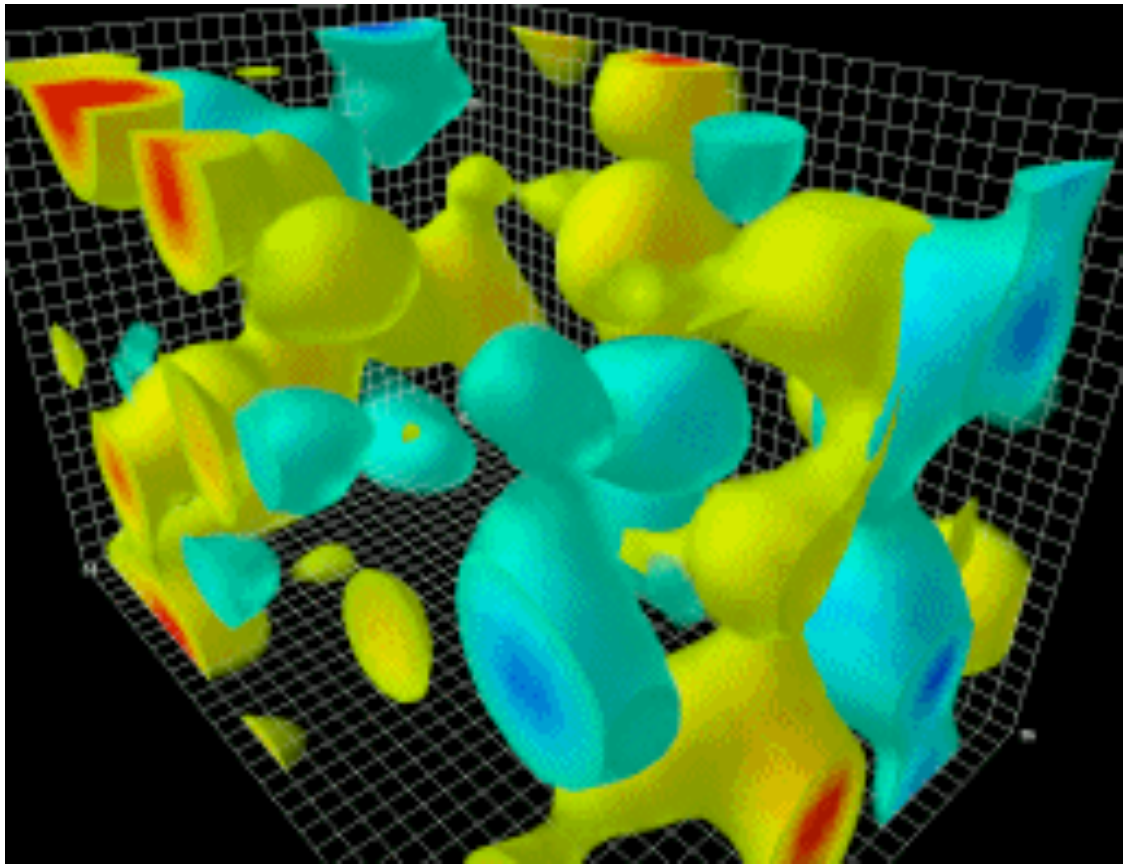
- Recent results
- Beam scan program

3) Future upgrade programs

High-Energy Nuclear Collisions

Search for Local Parity Violation

in High Energy Nuclear Collisions



Animation by *Derek Leinweber*

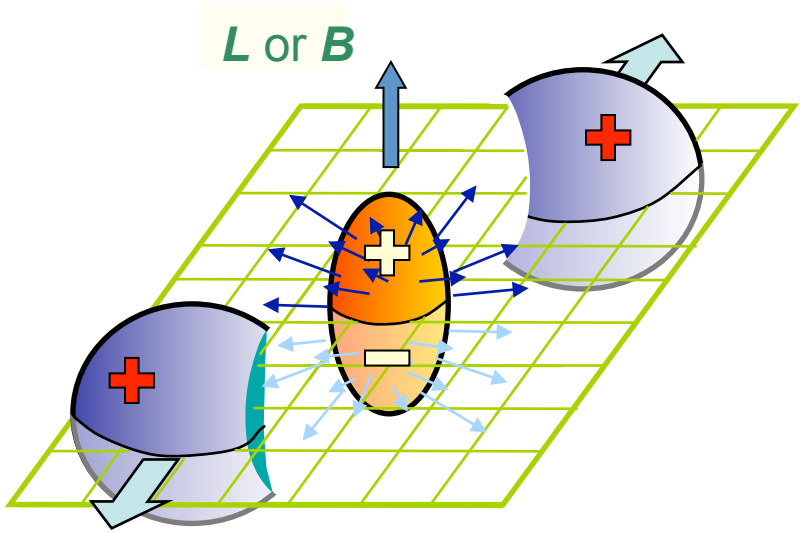
Topological transitions have never been observed *directly* (e.g. at the level of quarks in DIS). An observation of the *spontaneous* ***strong***, ***local*** **parity violation** would be a clear proof for the existence of the physics.

Chiral Magnetic Effect:

Kharzeev, PL ***B633*** 260 (06).
Kharzeev, *et al,* NP ***A797*** 67(07).
Kharzeev, *et al,* NP ***A803*** 227(08).
Fukushima, *et al,* PR***D78***, 074033(08).

Search for Local Parity Violation

in High Energy Nuclear Collisions

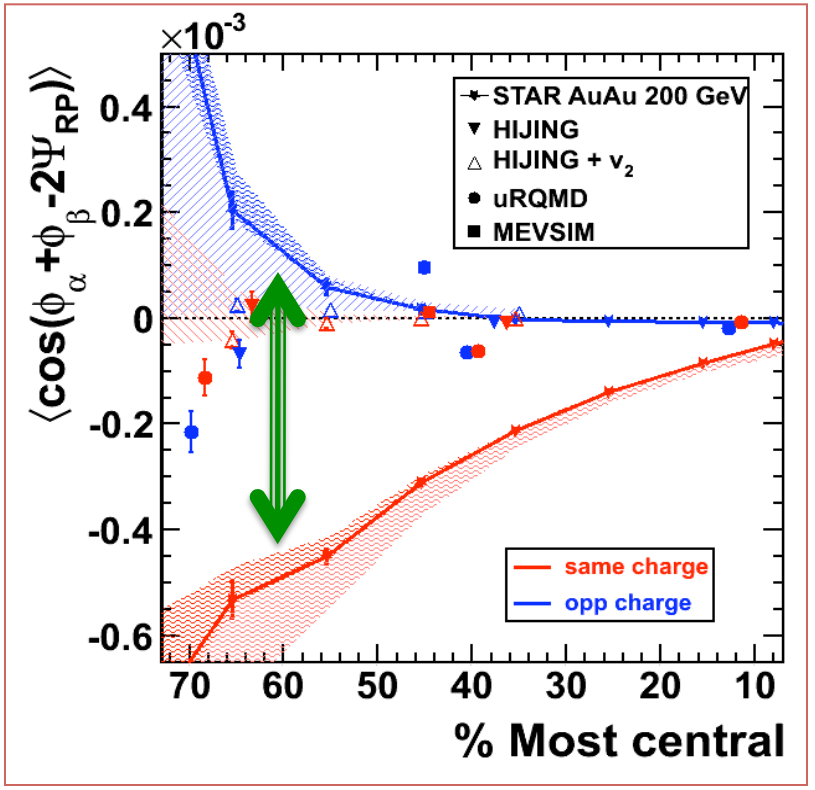


$$\left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{RP}\right)\right\rangle$$

Parity even observable

Voloshin, PR C62, 044901(00).

STAR; arXiv: 0909.1739 (PRL); 0909.1717 (PRC).

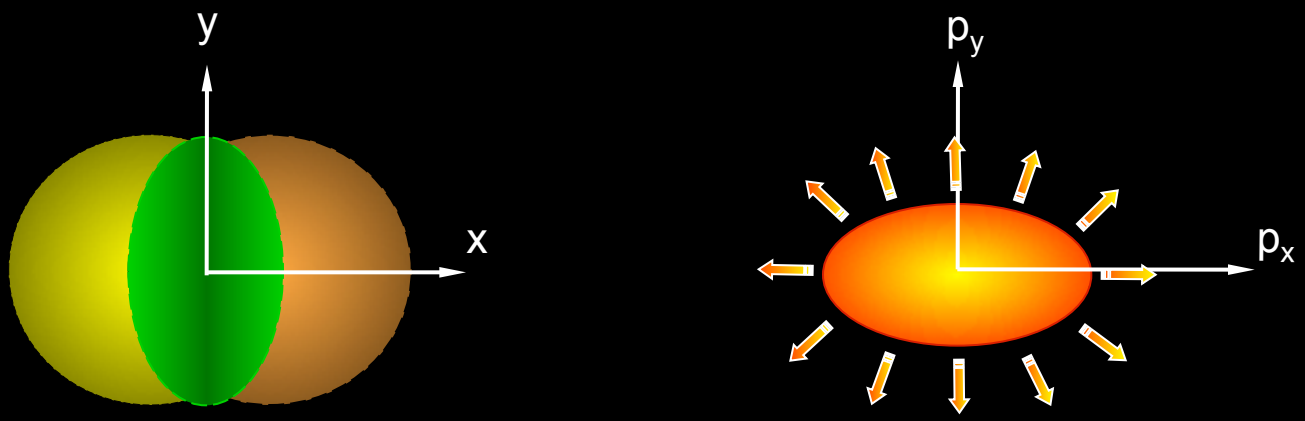


The separation between the same-charge and opposite-charge correlations.

- **Strong external EM field**
- ***De-confinement* and *Chiral symmetry restoration***

Anisotropy Parameter v_2

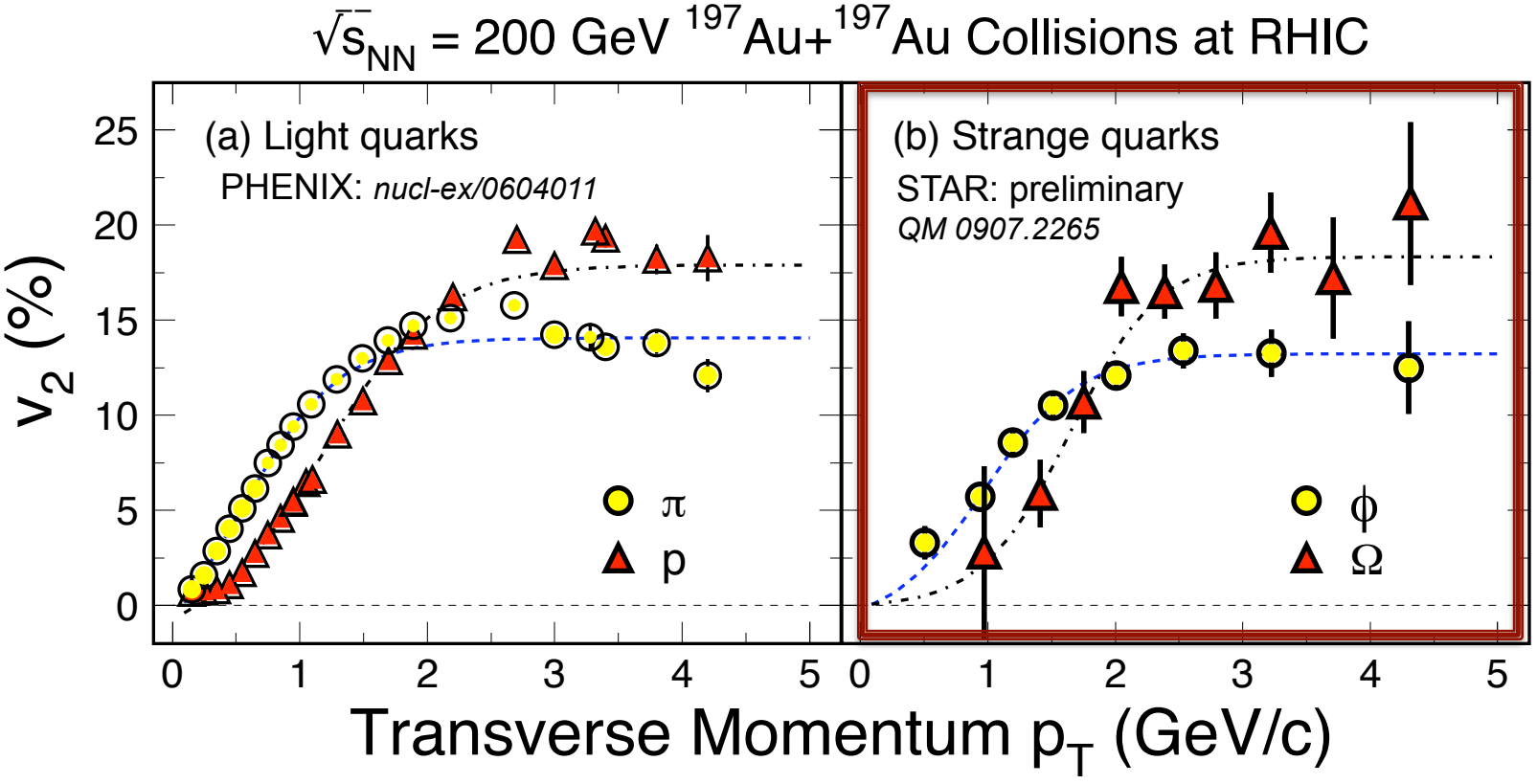
coordinate-space-anisotropy ⇨ momentum-space-anisotropy



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

Partonic Collectivity at RHIC

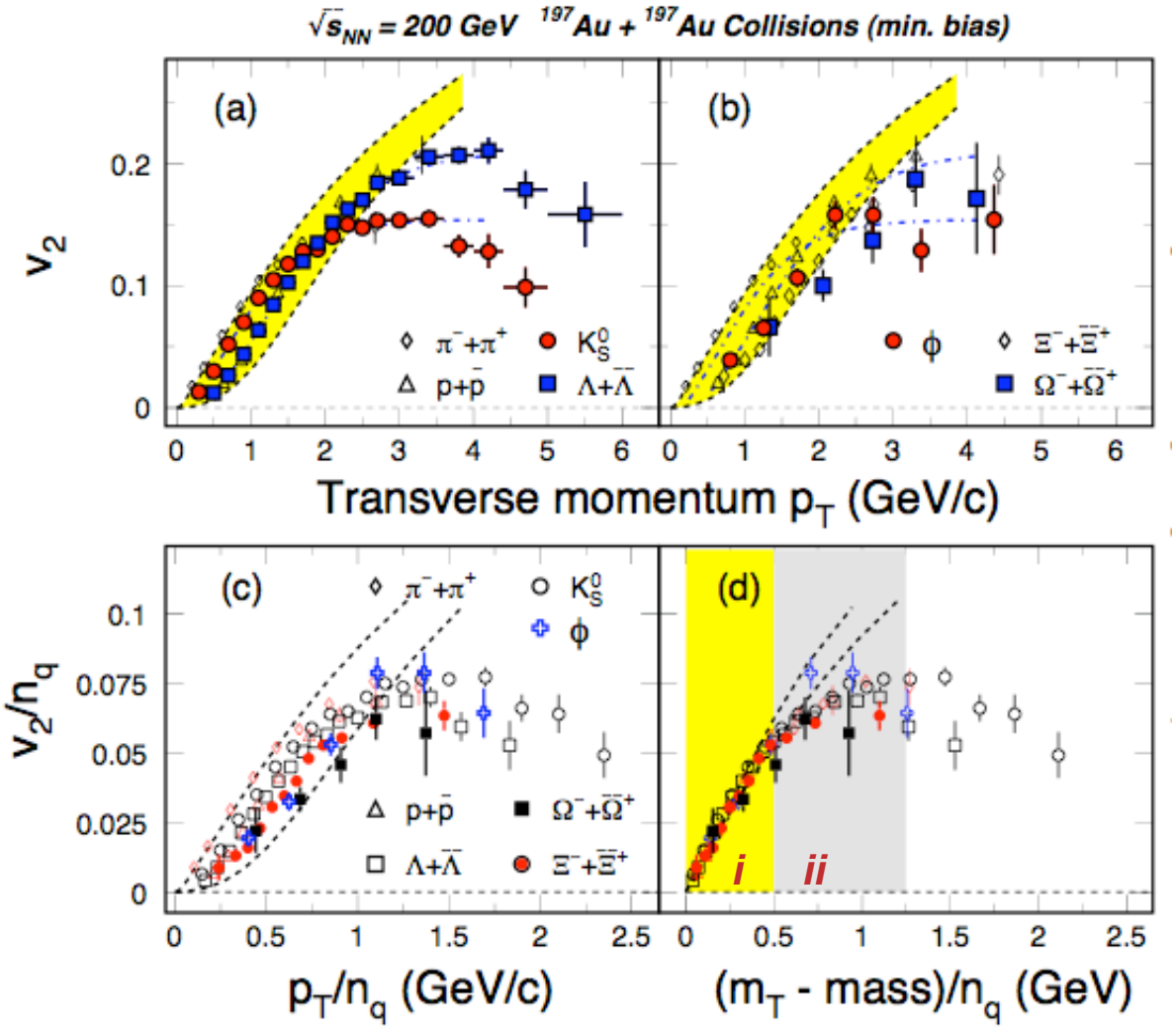


Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks ordering***

=> Collectivity developed at partonic stage!

=> De-confinement in Au+Au collisions at RHIC!

Collectivity, De-confinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

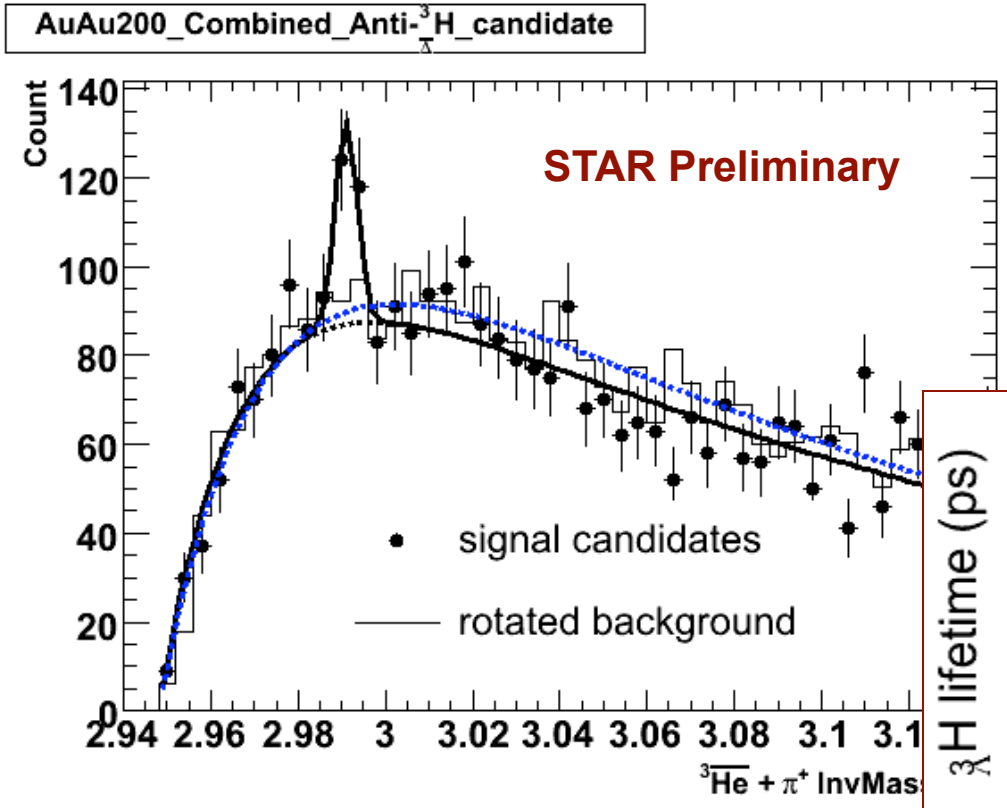
➪ **n_q-scaling**
novel hadronization process

➪ **Partonic flow**
De-confinement

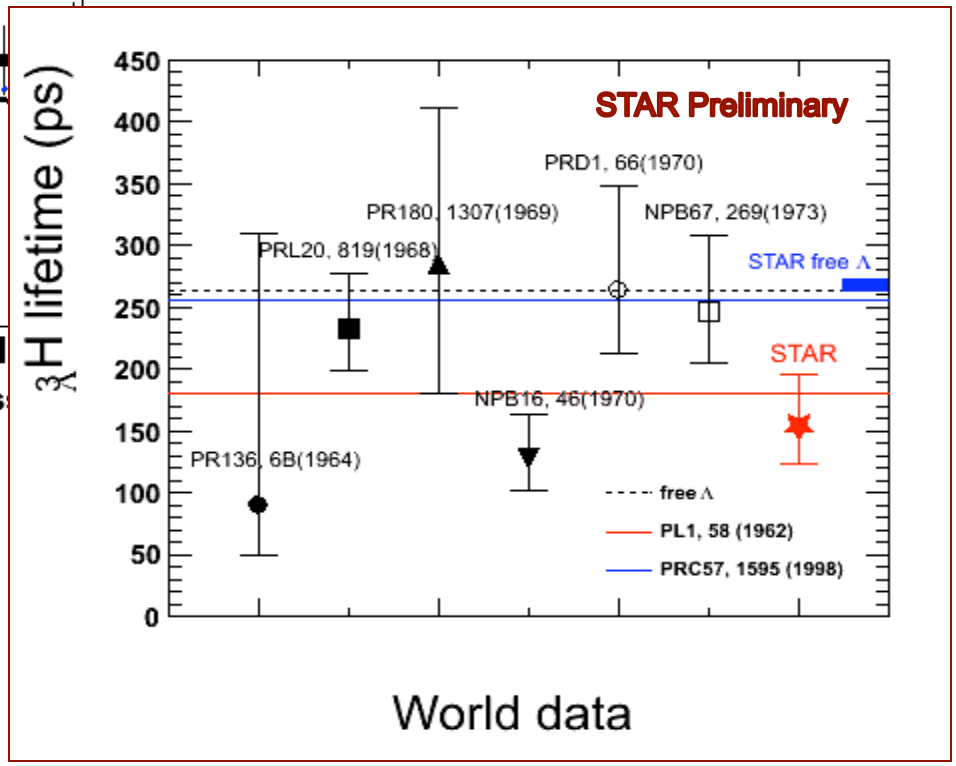
*PHENIX: PRL **91**, 182301(03)*
*STAR: PRL **92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

First Observation of $^{3}_{\Lambda}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$



200 GeV Au+Au collisions at RHIC



First observation of
an anti-hypernucleus

To be submitted to ***Science*** magazine

sQGP and the QCD Phase Diagram

In 200 GeV Au+Au collisions at RHIC, strongly interacting matter formed:

- **Jet energy loss: R_{AA}**
- **Strong collectivity: v_0, v_1, v_2**
- **Hadronization via coalescence: n_q-scaling**

Questions:

Is thermalization reached at RHIC?

- **Systematic analysis with dN/dp_T and dv_2/dp_T results…**
- ***Heavy quark and di-lepton measurements***

When (at which energy) does this transition happen?
What does the QCD phase diagram look like?

- ***RHIC beam energy scan***

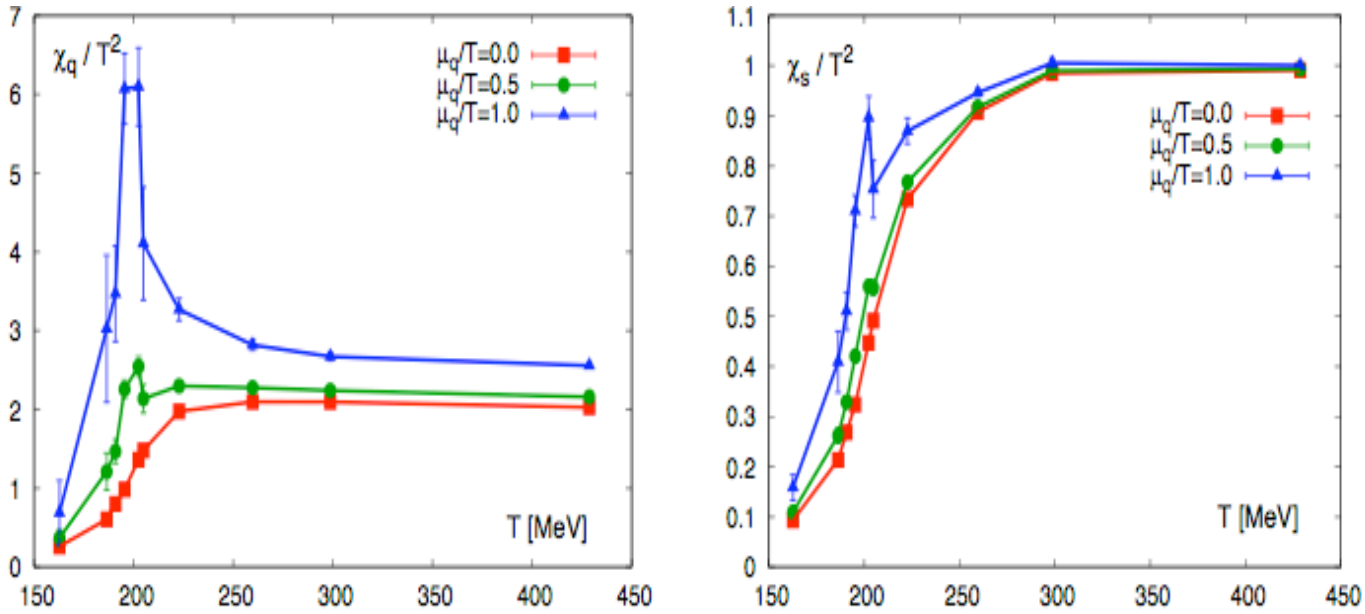
Run10 Physics Programs

RHIC cool down early Dec.

STAR shift starts Dec. 15th

Beam Energy (GeV)	25 cryo-week	30 cryo-week	20 cryo-week CR	Physics
200	10	10	10	Thermalization J/Ψ v_2, m_{ee}
62.4	4	4	5	
39	1	1.5		BES programs, T_E, phase boundary
27	2	4.5		
18	0	1.5		
11.5	2	2.5	**2.5**	
7.7	1	1	**2.5**	

Observables for QCD Critical Point



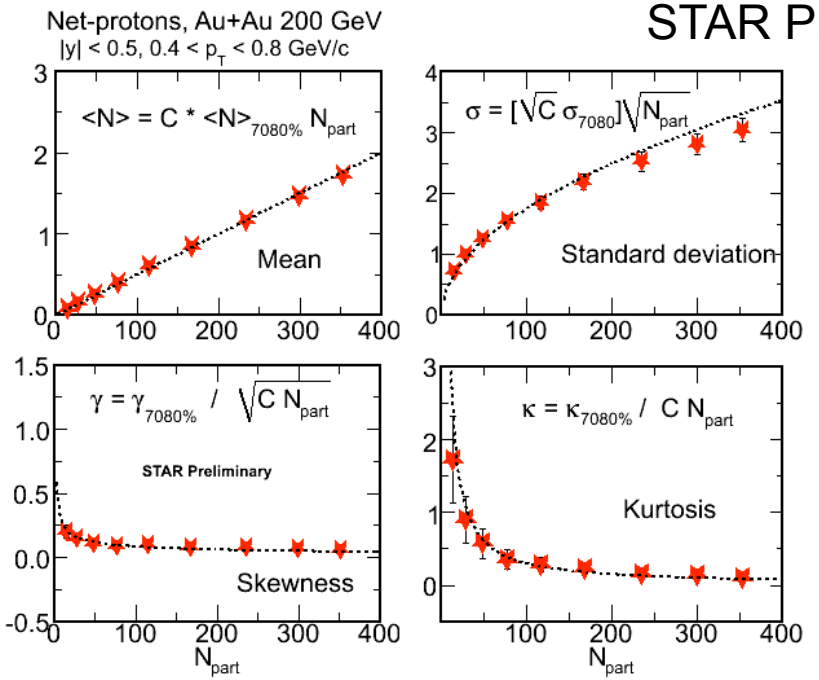
Event by Event:

1) The net-proton Kurtosis $K_p(E)$
2) Two proton correlation functions $C_2(E)$
3) Ratio of the d/p
4) Ratio of K/p

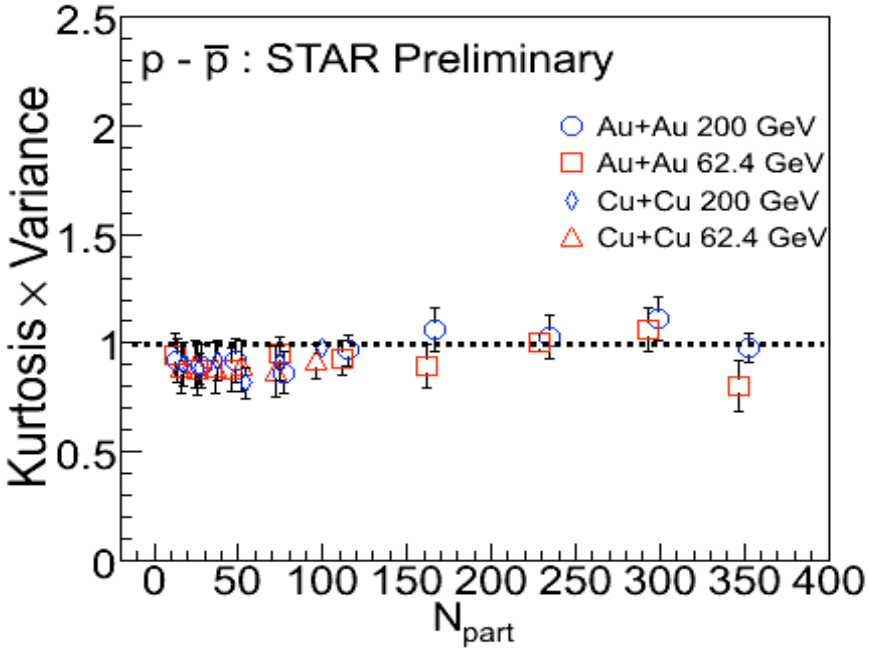
$$K_p = \frac{\langle N_p^4 \rangle - 3\langle N_p^2 \rangle^2}{\langle N_p^2 \rangle}$$

M. Cheng et al., PRD79, 074505(09);arXiv:0811.1006
*F. Karsch, INT, 08; M. A. Stephanov, PRL**102**, 032301(09)*

Higher Moments Analysis (BES)



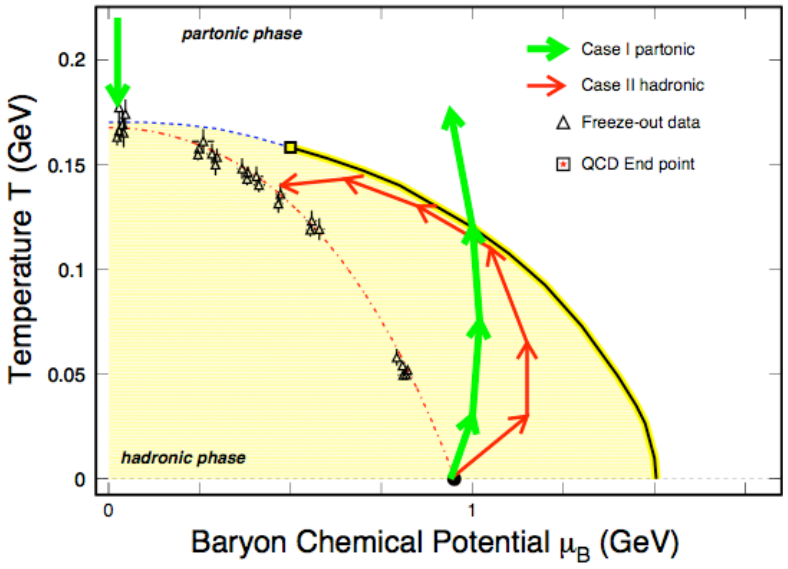
STAR Preliminary, QM09

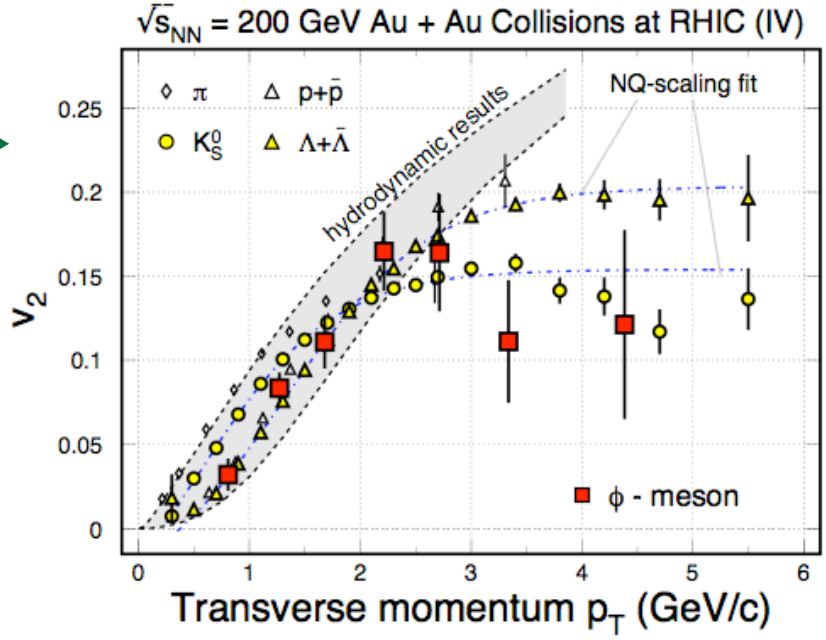


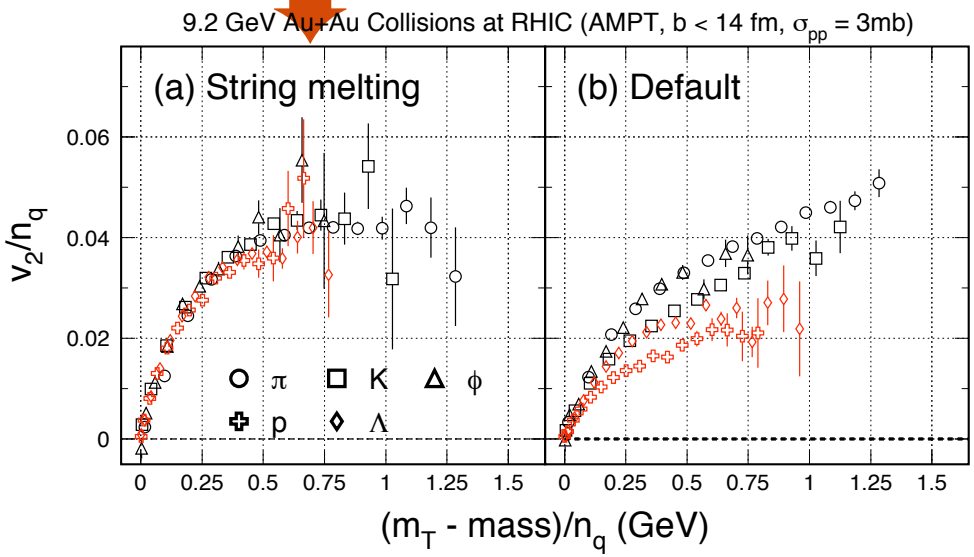
1) Higher moments are more sensitive to QCD critical point related fluctuation.

2) The 4th moment, Kurtosis, is directly related to the corresponding thermodynamic quantity: susceptibility of conserved quantum numbers such as Baryon number and strangeness.

Observable: Quark Scaling





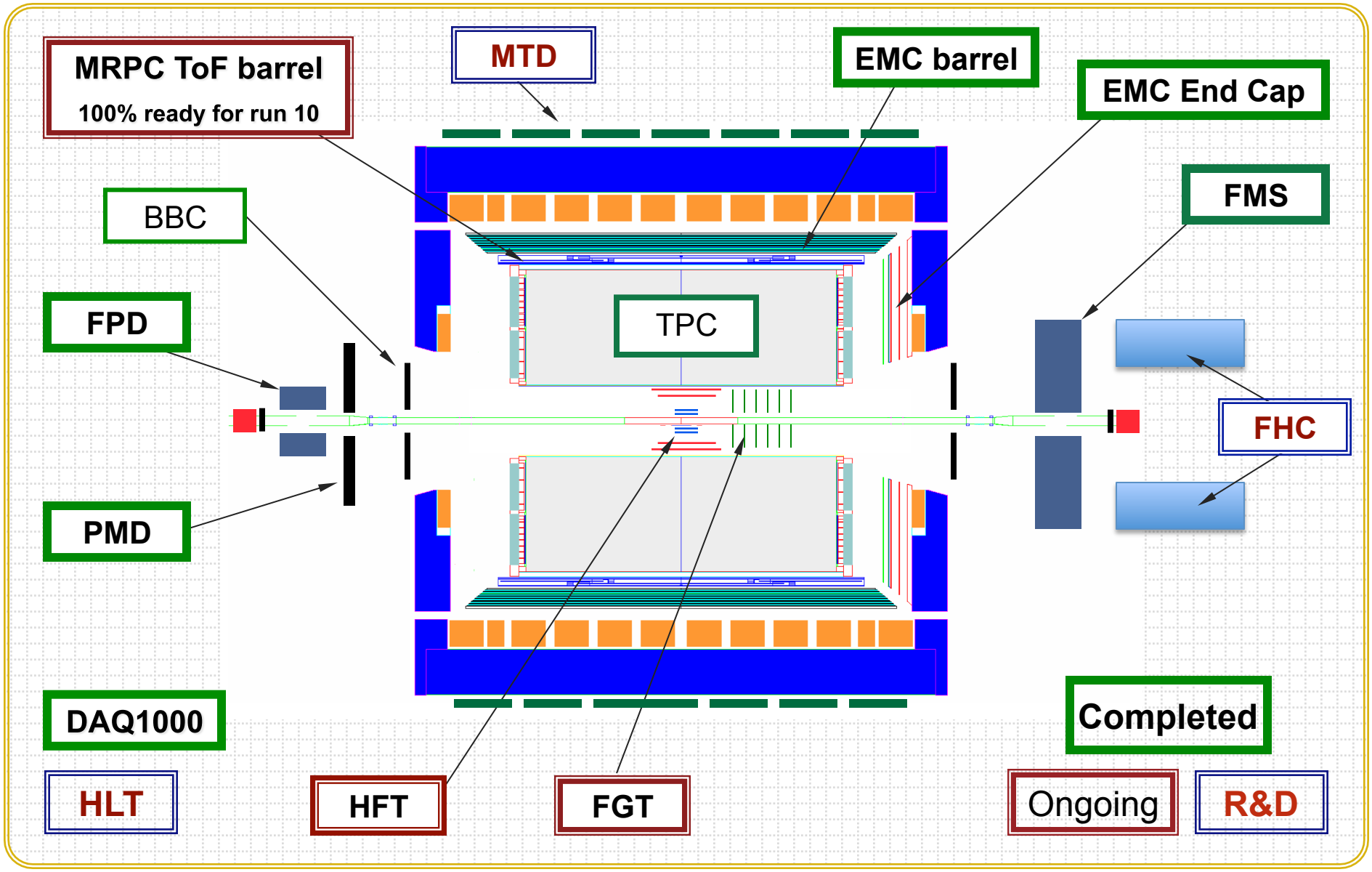


- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi,\ \pi\pi}$

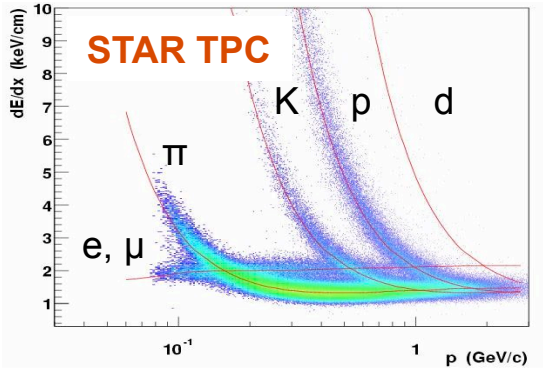
In the hadronic case, absence of n_q-scaling and the value of v_2 of φ will be small or zero.

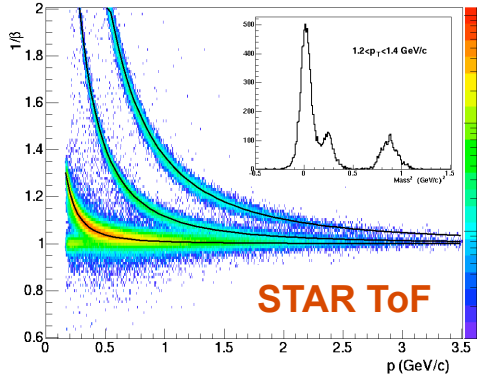
Future Upgrades

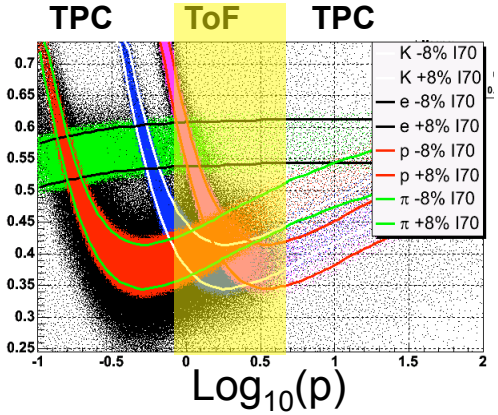
STAR Detector

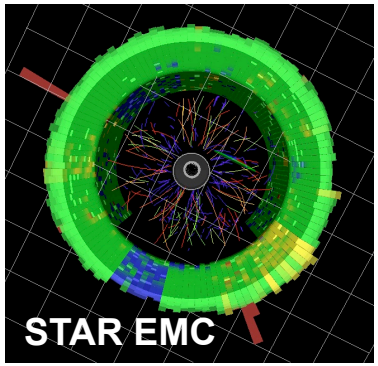


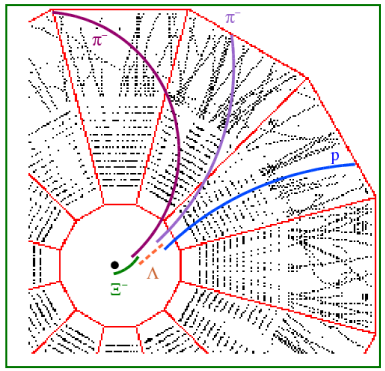
Particle Identification at STAR

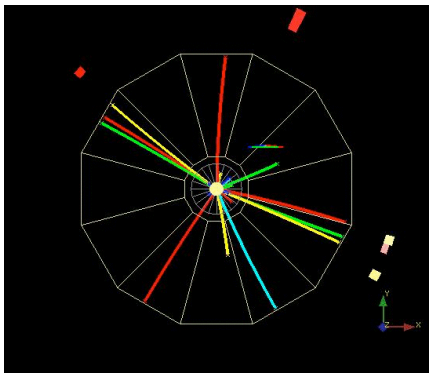


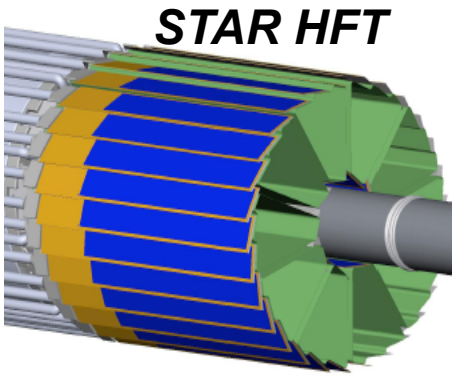










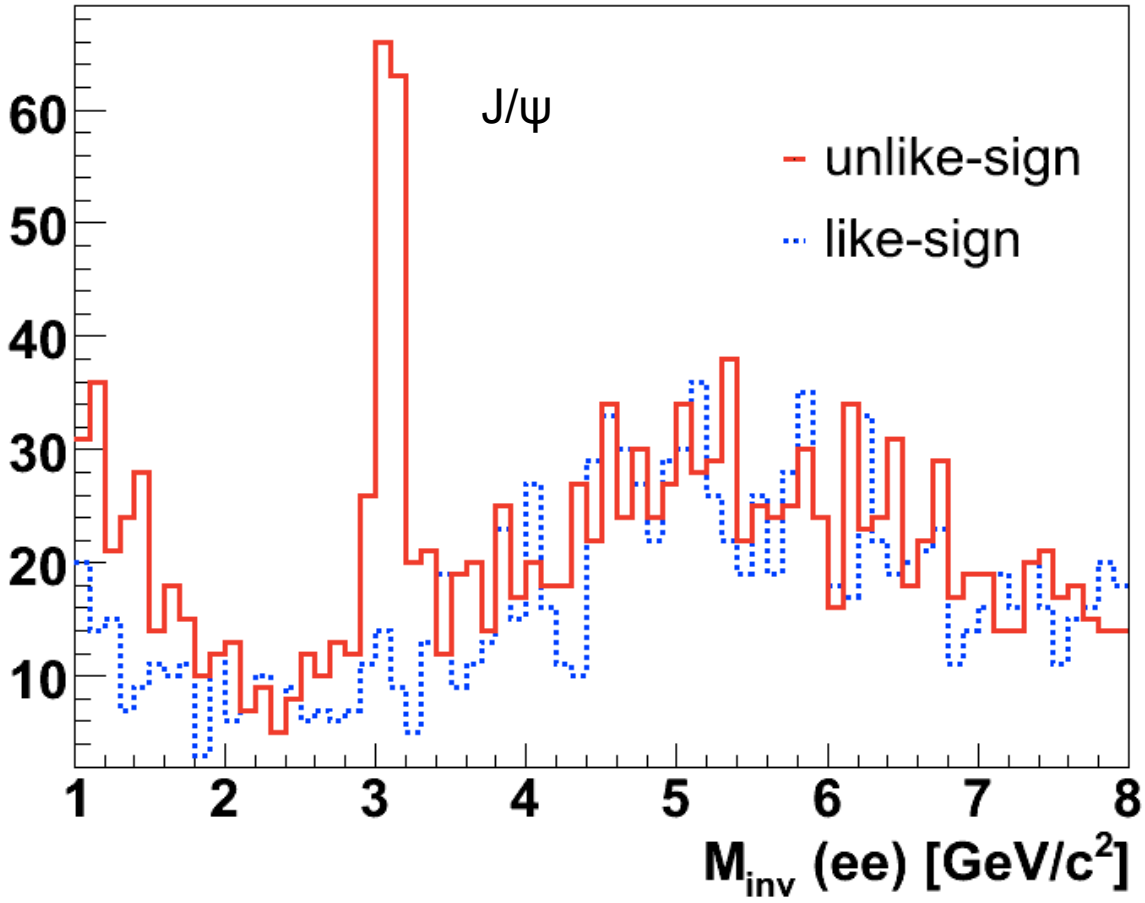


Neutral particles **Strange hyperons** **Jets** **Heavy Quark Hadrons**

Multiple-fold correlations among the identified particles!

STAR High Level Trigger

Run9 p+p 200 GeV, May 19 - 25



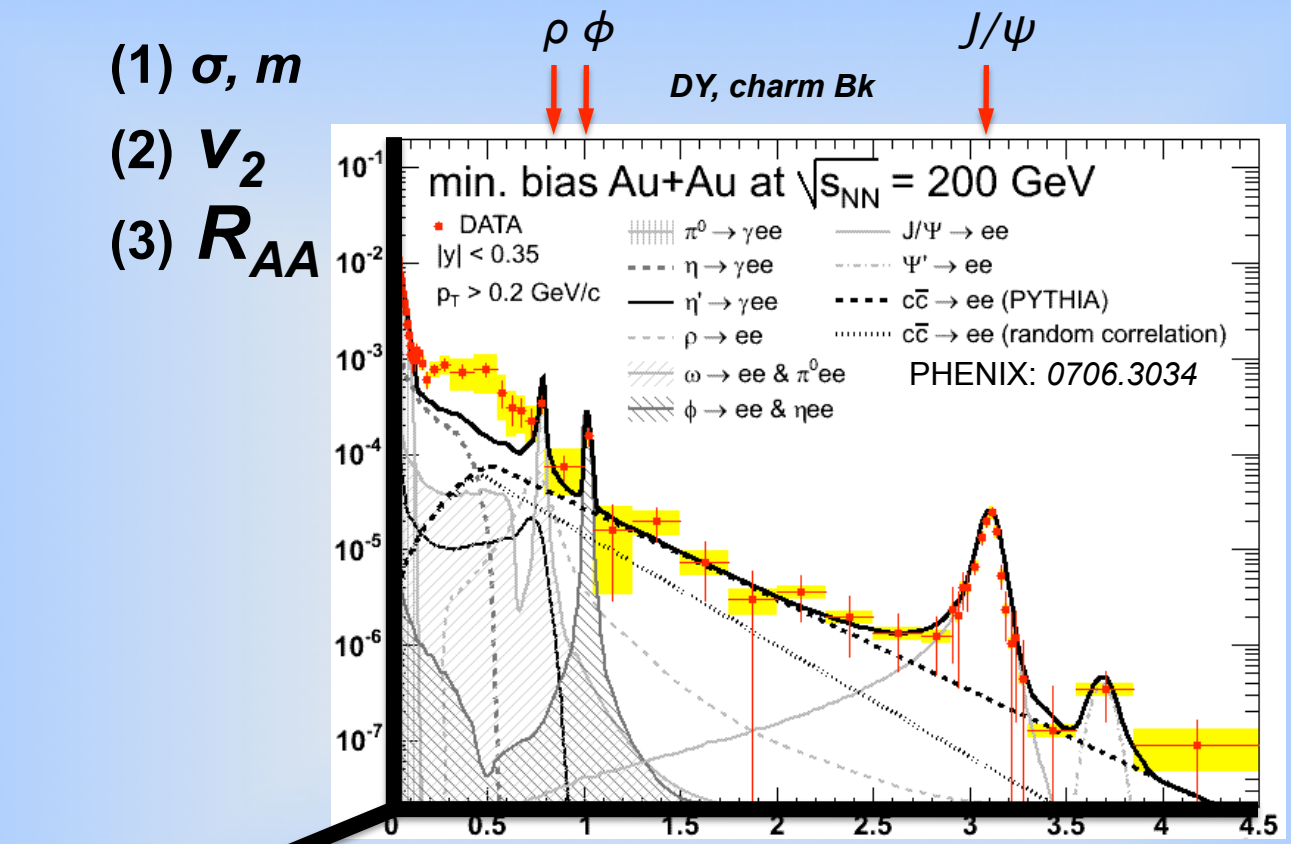
1) Fast filtering for quick data analysis. Run10: try J/ψ v_2
2) Online QA

The di-Lepton Program at STAR

(1) σ, m

(2) v_2

(3) R_{AA}

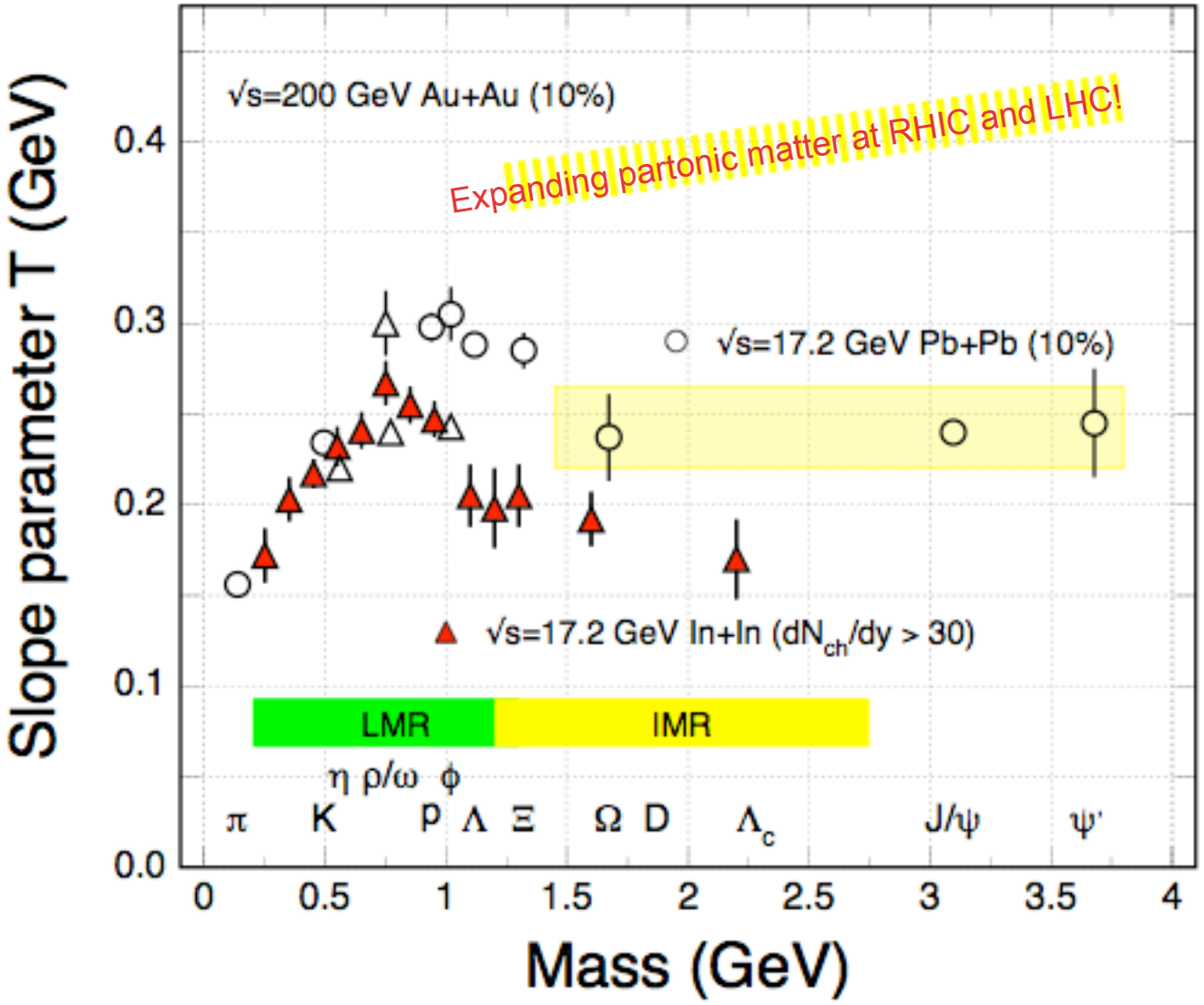


✓ **Chiral Symmetry Restoration**

✓ **Direct Radiation from The Hot/Dense Medium**

*** ToF Crucial for the physics.**

Direct Radiation



Di-leptons allow us to measure the direct radiation from the matter with partonic degrees of freedom, no hadronization!

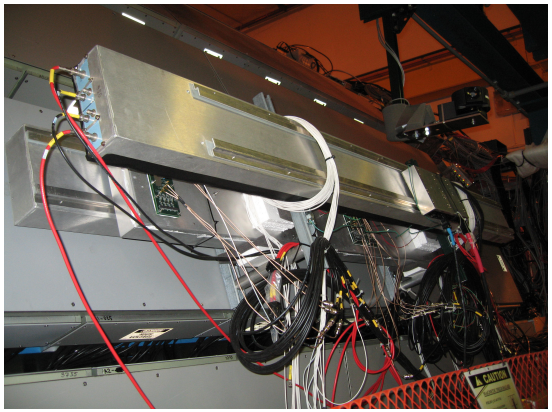
- Low mass region:
  $\rho, \omega, \phi \Rightarrow \mathbf{e^-e^+}$
  $m_{inv} \Rightarrow \mathbf{e^-e^+}$

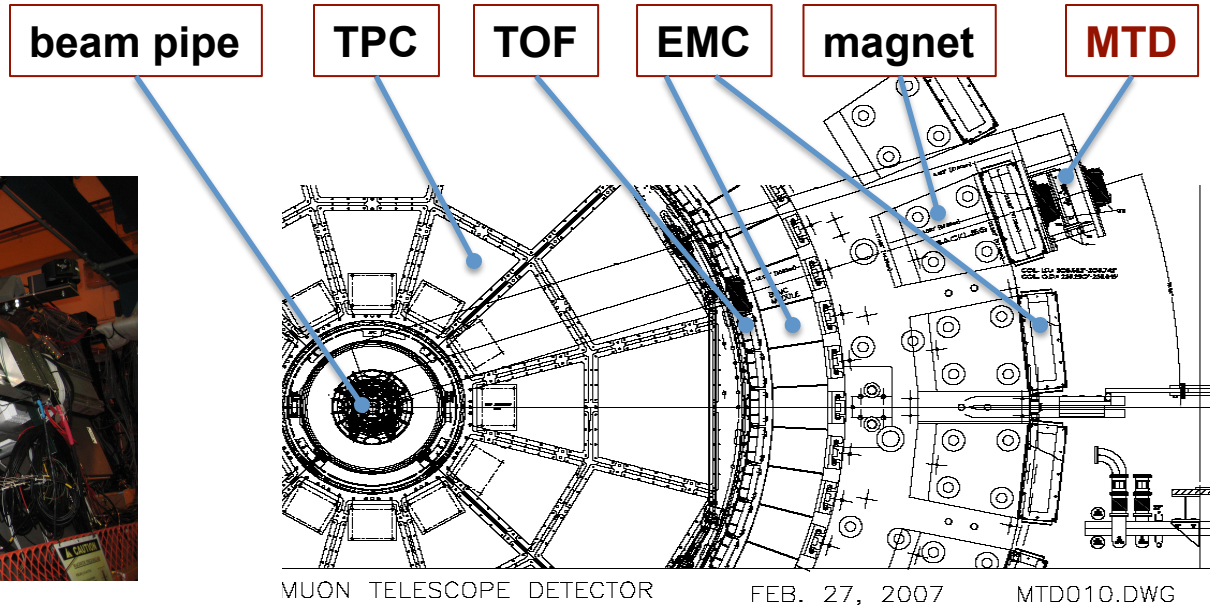
  medium effect
  Chiral symmetry

- High mass region:
  $\mathbf{J/\psi \Rightarrow e^-e^+}$
  $m_{inv} \Rightarrow \mathbf{e^-e^+}$

  Direct radiation

STAR: Muon Telescope Detector (2012)

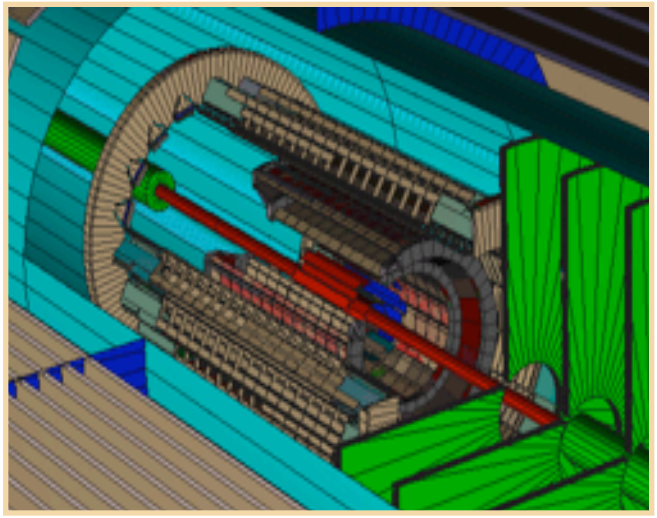


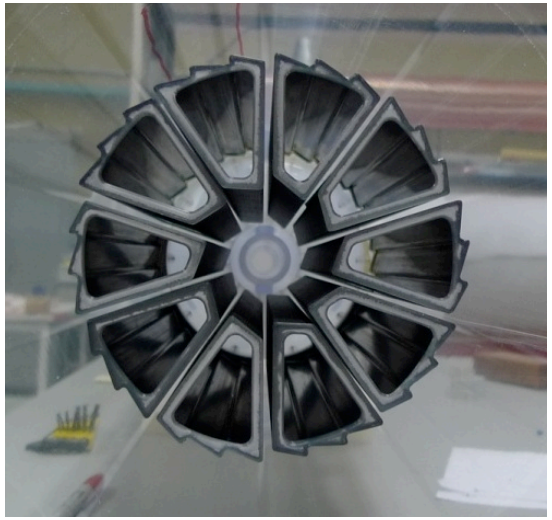


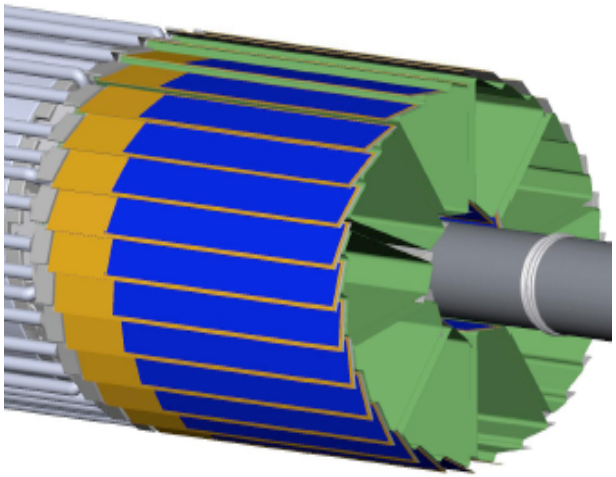
Muon Telescope Detector at STAR:

1) MRPC technology; μ_ε ~ 45%; cover ~60% azimuthally and |y| < 0.25
2) TPC+TOF+MTD: muon/hadron enhancement factor ~ $10^{2\text{-}3}$
3) For trigger and heavy quarkonium measurements
4) China-STAR collaboration: proposal reviewed in the collaboration

STAR Heavy Flavor Tracker (2014)





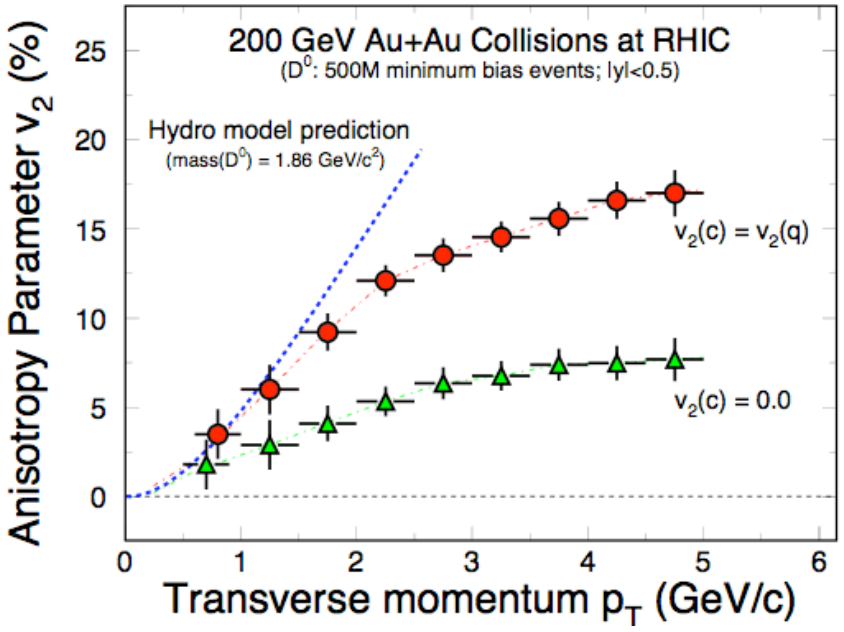


HFT: 2012-2014

1) Two-layer thin CMOS pixels; one-layer strips; SSD
2) First layer at 2.5 cm from beam pipe, 2pi coverage
3) Resolution~20μm

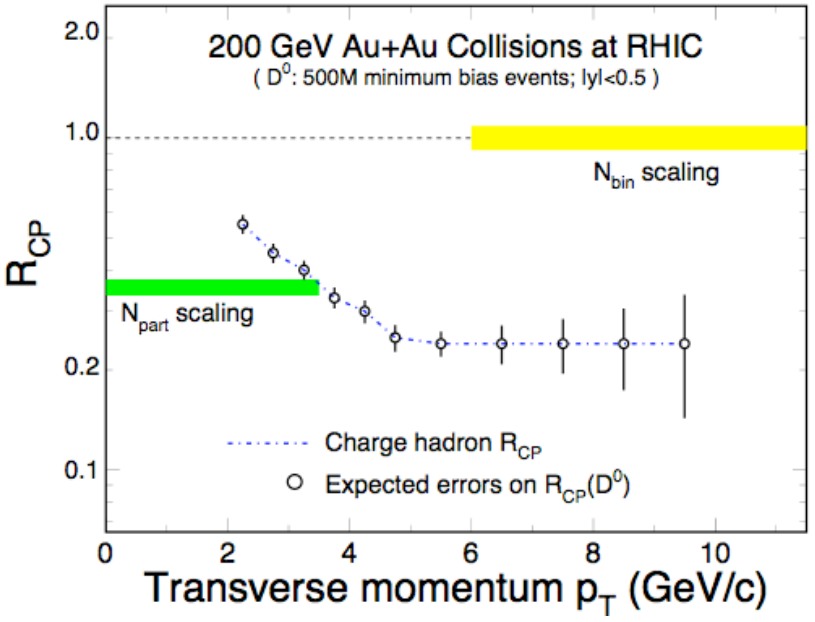
➔ **Measure down to low p_T ~ 0.5 GeV/c for open charm hadrons**

HFT: Charm Hadron v_2 and R_{AA}



- 200 GeV Au+Au m.b. collisions (500M events).
- Charm hadron collectivity ⇨ drag/diffusion constants ⇨

Medium properties!



- 200 GeV Au+Au m.b. collisions (|y|<0.5 500M events)
- Charm hadron R_{AA} ⇨

- Energy loss mechanism!
- QCD in dense medium!

Next Decade:
STAR QCD Physics Program

Spin Physics:

- 200 GeV: ***Δg*** inclusive and di-jets, γ-jet
- 500 GeV: ***sea quark*** helicity distributions
- 200/500 GeV: transverse spin phenomena

Low-x Physics:

- Study gluon-rich phenomena at RHIC
- Color glass condensate

Heavy Ion Physics:

- Thermalization at 200 GeV; direct gamma, m_{ee}
- QCD phase boundary, critical point
- In medium properties(?)